The 8th International Supercritical CO_2 Power Cycles Symposium
February 27 – 29, 2024, San Antonio, Texas
Paper 14

sCO_2 Waste Heat Recovery System Evaluation for Steelmaking Process

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Presenter Bio: Ladislav Vesely is a Research Assistant Professor at the Center for Advanced Turbomachinery and Energy Research (CATER), University of Central Florida. He graduated with his Ph.D. in 2018, and his research was oriented on the effect of mixtures on the sCO_2 power cycle. His work at UCF is oriented on power systems for WHR, CSP, energy storage, and nuclear applications. He has also been involved in several projects related to industrial decarbonization.

ABSTRACT

To maintain or reduce CO_2 emissions with the continually growing world population and related increasing requirements for energy, transportation, and energy-intensive industries (i.e., steel and iron, cement, aluminum, glass, food and beverage, paper, etc.) decarbonization is a key factor for current and future systems. The industrial sector contributes approximately 28 % of global CO_2 emissions. CO_2 emissions from energy-intensive industries can be reduced through several different approaches (i.e., direct - alternative fuel or energy source and Carbon capture systems; indirect - utilization of waste heat for the plant's own consumption) The waste heat recovery (WHR) represents a low-cost, zero-emissions power generation option with near-term deployment opportunities. This paper is focused on the evaluation of waste heat recovery systems for the steelmaking process. The steelmaking process has three sources of waste heat in three different steps where the waste heat can be utilized. The exhaust gas stream is only approximately 10 % of the available waste heat. However, the temperatures are between 200 and 1300 °C based on the process step and type of furnace. For this reason, the exhaust gas heat can be utilized by all potential power generation cycles such as the Organic Rankine cycle, Steam Rankine cycle, and supercritical CO_2 (sCO_2) cycle as a bottoming cycle. However, due to the large temperature range, potential retrofitting, and limited footprint, a sCO_2 waste heat recovery system can be an ideal candidate for utilizing waste heat streams in steelmaking processes. The paper is focused on the optimization of potential sCO_2 cycle layouts for a steel plant with several electric arc furnaces (EAF). The results show that sCO_2 power cycles can reach cycle efficiencies

above 35 %, which is higher than the corresponding Organic Rankine cycle (ORC) and Steam Rankine cycle (SRC). Results show higher performance of the sCO_2 cycle compared to ORC, SRC, and potential retrofitting into the current steel plants.

INTRODUCTION

Energy, transportation, and industrial productions (e.g., steel, cement, aluminum, etc.), and associated pollution, are increasing with the growing population. Pollution and CO_2 emissions have a negative effect on the planet's ecosystem. With continually growing global population and related increasing requirement for energy and transportation, decarbonization is a key factor for current and future system to maintain similar or lower level of emission, especially CO_2. According to data from 2021, the overall world CO_2 emission was approximately 35 billion tons CO_2, where North America generated approximately 17 % of the total CO_2 emissions [1] (Figure 1).

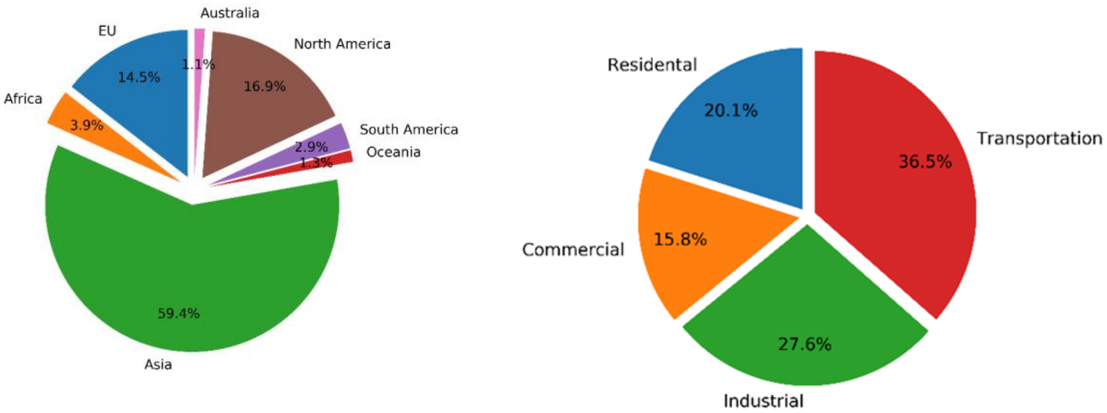

Figure 1.: Annual CO_2 emissions by region (left); Annual CO_2 emissions in US by sector (right) in 2021.

The 17 % of CO2 emissions generated by the North America is equal to 5.78 billion tons of CO_2 [1]. Further, the US produced approximately 4.6 billion tons of CO_2, which is approximately 85 % of CO_2 emission produced in the North America [1,2] and approximately the same amount as produced in the European Union (4.95 billion tons of CO_2 [1]). To effectively reduce or eventually eliminate emissions, a multifaceted approach is needed to break down and address the underlying causes of climate change [2].

In the last several decades, research has mainly focused on the reduction of CO_2 emissions from energy production and the transportation sector. However, CO_2 emissions are not only generated in these sectors. CO_2 emissions from the energy-intensive industries (e.g., steel, cement, aluminum, glass, etc.) produced approximately 28 % of total CO_2 emissions, the second highest production of CO_2 emissions after the transportation sector (approx. 36 %) [2] (see Figure 1). For example, the global iron and steel production in 2021 was estimated to be 1.9 million tons of raw steel [3,4], with China representing 60 % of total raw steel production. The US production of the steel, cement, and aluminum in million tons per year for 2021 is shown in Table 1.

Table 1.: The production of the steel/iron, cement, and aluminum for 2021 in the US.

	Aluminum	**Iron and Steel**	**Cement**	
Production	0.86	86 (steel); 22 (iron)	93	million tons per year
Capacity	1.69	-	100	
Reference	[5]	[4]	[6]	

There are several different approaches to reduce CO_2 emissions in each sector.

Decarbonization of industrial processes can be accomplished via a direct and indirect approach. The direct approach is to replace the heat source with a low emission fuel or renewable heat source. However, the heat source must have the ability to provide the high-temperature heat required for the process. The indirect approach is to utilize waste heat from the process to generate electricity for the plant's own consumption [7-11]. The waste heat in energy-intensive industries qualifies as a byproduct part of the system and is not recognized as the primary source of reducing emissions. However, the waste heat can be used as a secondary source to reduce required power (fuel) for the system operation with independence of type of fuel. The required power consumption for the energy-intensive industries (electricity, heat source – fuel, etc.) can be reduced, thus reducing the associated CO_2 emissions. A short-term perspective implies that the indirect approach is the most economical way. Industrial sectors have the potential to recover up to 34 % of available waste heat [9]. With the accurate definition and utilization of the waste heat, the waste heat can increase the power generated while minimizing impacts on current processes and reduce external sources of power to meet plant needs.

This work focuses on the design and optimization of a waste heat recovery system for the steel-making process based on the sCO_2 power cycles. This paper provides a detailed description and qualification of the potential utilization of the waste heat for the steel-making process, especially from electric arc furnaces (EAF) as well as a comparison and selection of potential waste heat recovery systems based on the waste heat source.

IRON AND STEEL PROCESS DESCRIPTION

The of iron and steel process can be divided into three separate phases: ironmaking, steelmaking, and metal casting. The process is illustrated in Figure 2 ([12,13]). In each step, large amounts of heat are generated and often wasted to the atmosphere in the form of hot iron and steel slag.

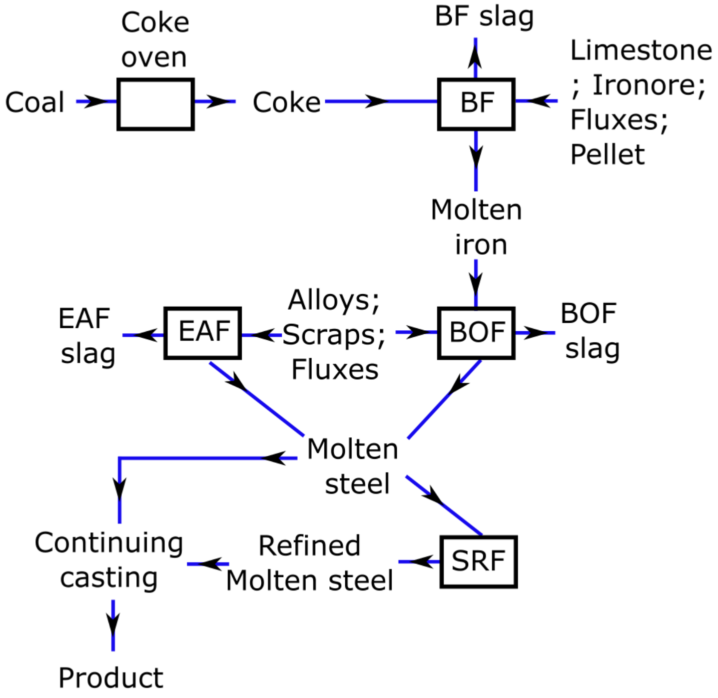

Figure 2: Steel plant block flow diagram.

The ironmaking process (Step 1 of the process) is the main process to produce molten iron (crude iron) to create new steel. The typical operation temperature for the required chemical reactions is approximately 1600 °C – 1750 °C [12]. This process is typically divided into two distinct steps, namely the creation of coke from coal in the coke oven and the formation of molten in the blast furnace (BF).

The steelmaking process (Step 2 of the process) can be divided into two independent procedures, based on the material source (crude iron and scraps). The Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF) are two furnaces typically used to carry out the steelmaking process:

- The basic oxygen furnace (BOF) is currently the dominant process for steel production globally, accounting for 50 - 60 % of the world's steel production [12]. In contrast, in the US, EAFs account for 70 % of total steel production and is projected to rise to 90 % by 2100 [14].

- The EAF operates with temperatures similar to that of the BOF.

The metal casting process utilizes molten steel (Step 3 of the process), see Figure 2. The iron and steelmaking process has two sources of the waste heat in three different steps where the waste heat can be utilized:

- primary waste heat source (exhaust gas and solid (slag) streams)

- secondary waste heat source (metal casting exhaust gas stream)

The exhaust gas stream is only approximately 10 % of the available waste heat. The exhaust gas can be utilized from the coke oven, BF, BOF and EAF. The exhaust gas temperature range for each stream is shown in Table 2. The composition of the exhaust gas stream is different based on the oven/furnace. The typical substances are CO_2, N_2, CO and H_2. The typical exhaust gas compositions are listed in Table 2.

Table 2.: Primary waste heat source parameters and Exhaust gas composition [8].

	Exhaust temperature range		H_2	CO	CO_2	N_2	CH_4	C_2H_6	H_2O
	K		%						
Coke oven	1253.15	473.15	52	4	2 {8}	{70}	37	5	{22}
Blast furnace	703.15	403.15	3	26	21 {26}	50 {68}			{5}
Basic oxygen furnace	1973.15			73	16	8			
Electric arc furnace	1473.15	477.15	11	18	14	57			

WASTE HEAT RECOVERY SYSTEM

The waste heat is qualified and divided based on temperature into three ranges (i.e., low, medium and high temperature range) [15-18]. The typical waste heat temperature is up to 1400 K (high temperature range) [8-10]. The low temperature range is up to approximate 573 K and the medium temperature range is between 573 and 973 K [17,18]. The waste heat can occur in various states based on the heat source (i.e., solid, liquid or gas). According to heat source and type of the waste heat, different types of the power conversion system can be used [19]. The type of the power conversion system depends on the waste heat temperature and maximum amount of the available heat. The most common power systems are the organic Rankine cycle (ORC) [20,21], the steam Rankine cycle [22,23], and the sCO_2 cycle [24,25]. However, the type of the system also depends on the size and potential retrofitting into the current system [7]. The main advantages and issues for SRC, ORC and sCO_2 cycle are shown in Table 3.

Table 3: Advantages/disadvantages of power conversion system for industrial waste heat.

ORC		SRC		sCO_2	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**	**Advantages**	**Disadvantages**
Current use	Max. operating temperature 400 C	Current use	Water requirement	High efficiency	Under develop
Footprint	Working medium	Working medium	footprint	Footprint	Pressure
Size	Price	Price	Size	size	Price
Retrofitting			Retrofitting	No water requirement	Materials
				Turbomachinery	HEX
				Retrofitting	

The sCO_2 power cycle has many benefits when compared to SRC and ORC. Because of this, the sCO_2 power cycle has been selected as a potential WHR system. The sCO_2 power cycle can be designed based on several cycle layouts. Based on the cycle layout definition, the sCO_2 power system has the capability to use a single or multi-heat source.

Each cycle layout consists of a primary heat exchanger (PHX), a cooler (CH) designated (using water or air, according to local requirements, regulations, and cooling availability [26]), recuperative heat exchanger (RHX), compressor (C), and turbine (T). All configurations presented in this work use air as the cooling medium. The CH is designed as a crossflow heat exchanger, which consists of bundles of tubes where the air is forced to flow over the tube surface using fans [27].

The sCO_2 power system layouts selected in this study are the simple Brayton, Recuperated, Re-compression, and Split expansion cycles. Recuperated and Re-compression cycle layouts are listed in Figure 3.

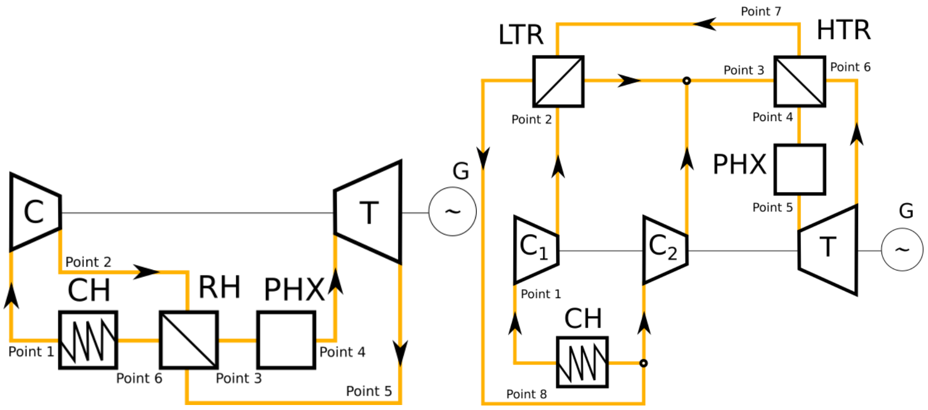

Figure 3: Recuperative (left) and Re-compression (right) cycle layouts.

MODEL DESCRIPTION

The sCO_2 waste heat recovery system was simulated using an in-house computer code based on the Python programing language [28,29]. NIST Reference Fluid Thermodynamic and Transport Properties database, Version 9.1. [30] and CoolProp [31] (Open-source Thermophysical Property Library) were used as source of the properties for optimization.

The main input parameters are listed in Table 4. The assumptions for detailed optimization are as follows:

- Waste heat stream temperature is 1473 K (EAF – see Table 2)
- Exhaust gas flow is uniform and pressure drops are not considered
- Average ambient air temperature is defined as 27 °C, and the minimal temperature difference between air and CO_2 streams is 5 K
- The system is designed for 4 MWe net power
- The pressure drops are not considered in the calculation for all cases
- The generator efficiency is 96 %, clutch efficiency is 95 % and gearbox efficiency is 93 % [7]

Table 4: Assumptions and boundary conditions.

Parameter	Lower	Upper	
Pressure ratio	2.6	4.0	-
Turbine inlet pressure	20	30	MPa
Turbine inlet temperature	823.15		K
Compressor inlet temperature	306		
Turbine efficiency	90		%
Compressor efficiency	69		
Recuperator effectiveness	90		

RESULTS

The four cycles mentioned above were investigated. The cycle optimization has been done based on input and boundary conditions/assumptions listed in Table 4. The simulations are divided into the several steps. The first step was to define the monitoring parameters (i.e., net power and added heat). The cycle efficiency was not considered as monitoring/optimized parameters due to waste heat recovery systems definition. The main parameters considered to select the most useful cycle layouts were the net power (electrical power – depends on the plant's own consumption) and added heat (PHX effectiveness that define potential heat transfer from waste stream).

The second step was the simulation based on parameters listed in Table 4 to provide potential regime with highest net power and corresponding added heat. Each cycle required and can provide different amount of heat or power. The added heat has direct impact on the iron and steel processes. However, not every process will be affected by WHR. The WHR for EAF process will utilize only exhaust gas that is not used anywhere in the process. Hence, the added heat is not the most critical parameter for the cycle layout selection. However, the added heat is a limitation parameter due to potential heat availability in the exhaust stream. The added heat distribution for the pressure ratio between 2.6 and 4, and the turbine inlet pressure between 20 and 30 MPa is shown in Figure 4. The net power distribution for the pressure ratio between 2.6 and 4, and the turbine inlet pressure between 20 and 30 MPa is shown in Figure 5.

According to results, the recuperated layout can provide the same net power as the simple Brayton layout with lower amount of added heat, due to the recuperative heat exchanger. The lowest added heat requirement was for the split expansion layout (see Figure 4 D). However, the split expansion cycle will provide lower net power compared to the re-compression layout with same pressure ratio and turbine inlet pressure as the split expansion layout.

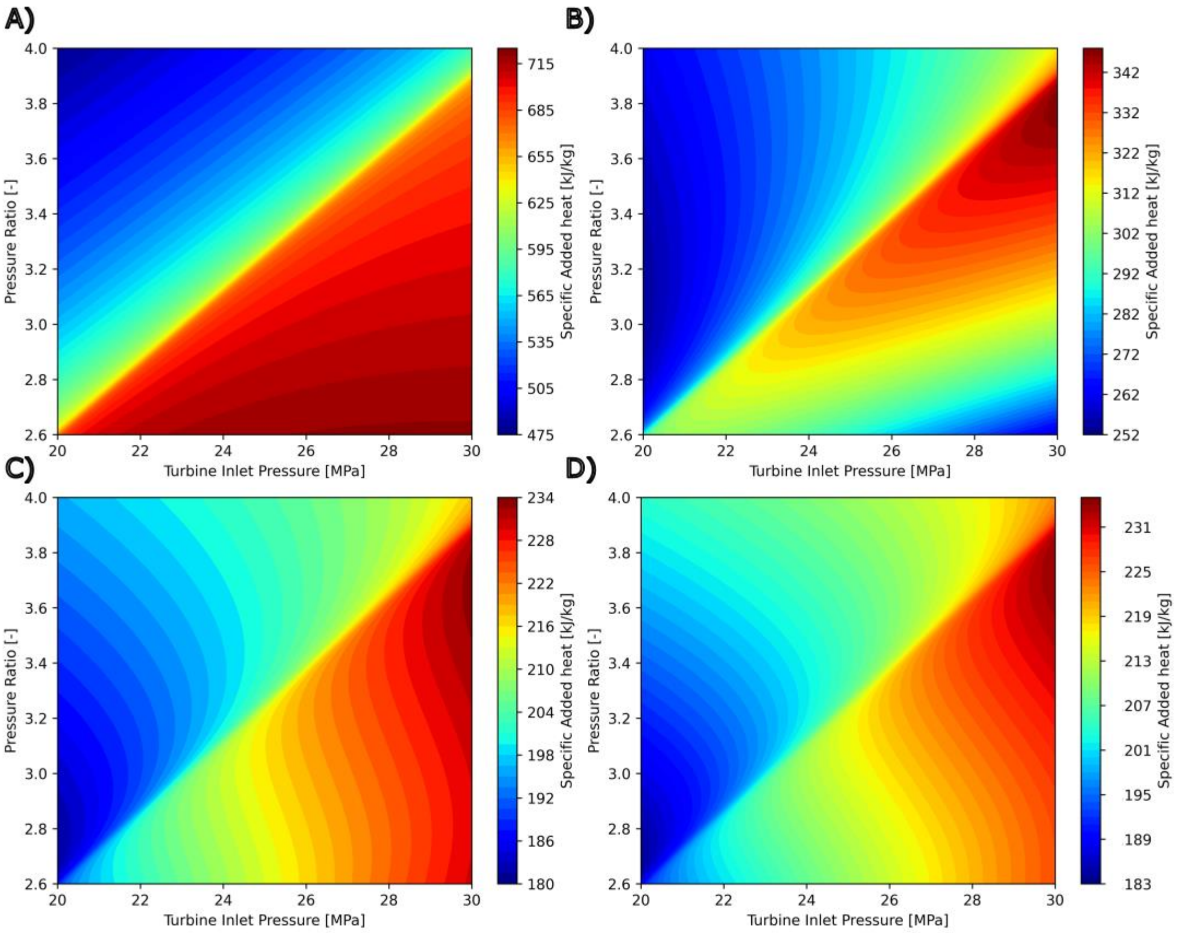

Figure 4: Specific added heat – A) simple Brayton; B) Recuperated; C) Re-compression; D) Split expansion cycle.

The last step of this study was the detailed optimization. The cycle layouts have been optimized to define which configuration is most suitable for the WHR in iron and steel making processes applications. The cycle optimization has been done based on input and boundary conditions in Table 4. The optimized results are listed in Table 5.

Table 5: sCO_2 WHR power cycles optimized results.

	Simple Brayton	**Recuperated**	**Re-compression**	**Split Expansion**	
$\boldsymbol{\eta_{th}}$	18.35	35.68	**39.15**	35.38	%
$\mathbf{W_t}$	6.59	6.59	6.03	6.2	MW
$\mathbf{W_c}$	1.75	1.75	1.22	1.35	
$\mathbf{Q_{in}}$	26.34	13.5	**8.62**	9.09	
$\mathbf{Q_{out}}$	21.5	8.7	3.34	3.76	
$\mathbf{Q_{reg}}$	0	12.76	12.84	17.39	
$\mathbf{W_{gross}}$	4.8	4.8	4.8	4.8	
$\mathbf{W_{net}}$	4	4	4	4	
$\mathbf{m_{sCO2}}$	39	39	37	39	kg/s

The results in Table 5 are for the compressor inlet temperature of 32.85 °C, TIT of 550 °C, and turbine inlet pressure 30 MPa. The pressure ratio is different for each investigated cycle layout. The simple Brayton and the recuperated cycle have a pressure ratio of 3.8. The re-compression cycle has a pressure ratio of 3.6, and the split expansion has a pressure ratio of 3.7. According to the optimized results, RCC cycle layout had the highest cycle efficiency and lowest required added heat for the same net power compared to other cycle layouts.

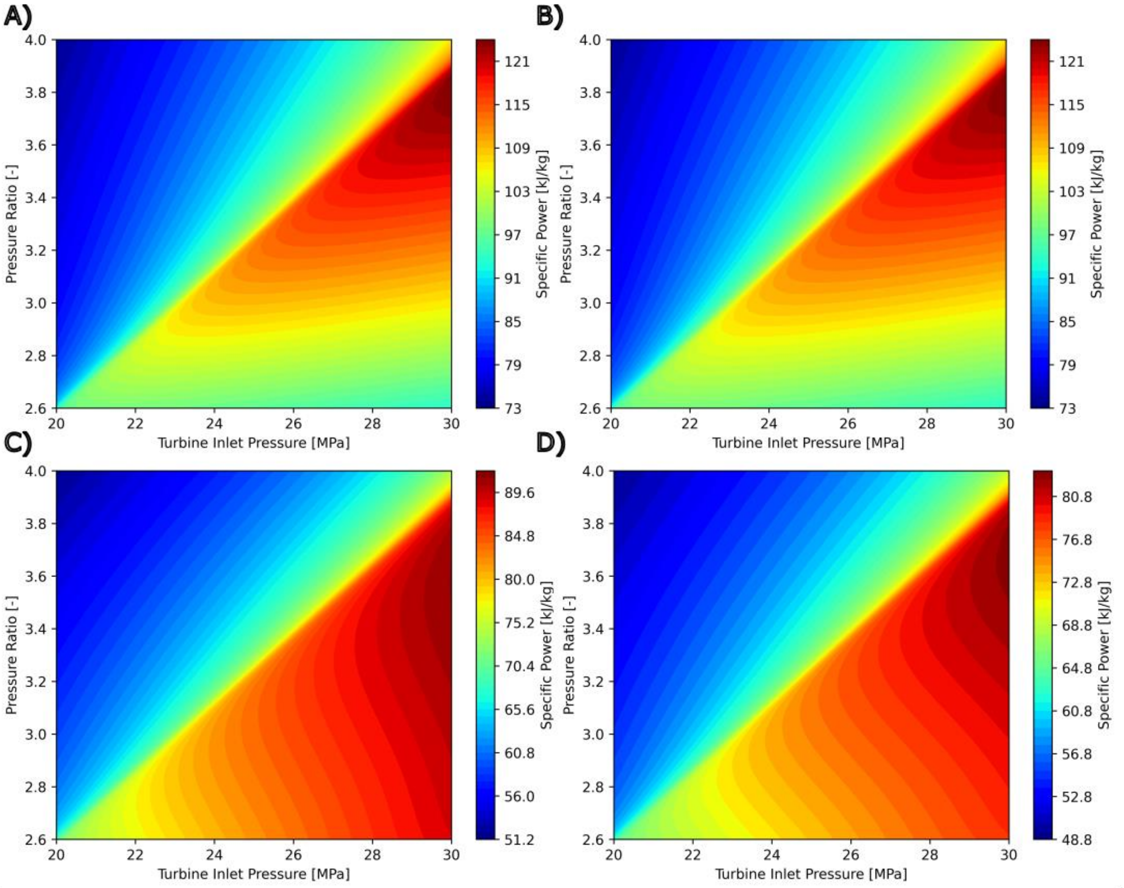

Figure 5: Specific net power – A) simple Brayton; B) Recuperated; C) Re-compression; D) Split expansion cycle.

CONCLUSIONS

This study evaluated the potential implementation of a sCO_2 WHR system for an iron and steel making processes application. The WHR system has potential impact on the decarbonization of the iron and steel making processes due to replacement of the current source of heat and power via the WHR that can produce power for the plant's own consumption. The work evaluated several potential sCO_2 power conversion cycle layouts (i.e., Simple Brayton, Recuperated, Re-compression, and Split-expansion) to utilize waste heat from the EAF exhaust streams.

The results show the potential to use sCO_2 power cycle as a waste heat recovery power cycle. According to the results, the cycle layouts investigated in this work have cycle efficiencies up to 39 % (the re-compression cycle). This cycle efficiency is higher compared to the ORC cycle and SRC cycle for similar operation parameters. However, the benefit of the sCO_2 power cycle conversion is its compactness and potential for retrofitting, and the sCO_2 cycle can generate more net power for lower added heat. The most promising cycle layout is the re-compression cycle. The split expansion can be also considered as potential cycle layouts. However, the results in

Table 5 are only for the sCO_2 TIT 550 °C which is the maximum operating TIT considered for this application. The sCO_2 turbine may be able to operate at higher TIT, which will increase potential net power and reduce the required added heat. However, higher TIT will require different material and potential turbine blades cooling, which will increase overall cost of the WHR unit.

Future work will focus on the detailed techno-economic analysis for cycle layouts investigated in this work and the detailed design of the PHX with optimization of the WHR unit on the highest potential PHX effectiveness.

DISCLAIMER

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